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LERWICK ANEMOGRAPH RECORDS 1957–70 AND THE OFFSHORE INDUSTRY

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Summary. Hourly mean winds from Lerwick Observatory for the 14 years 1957–70 are analysed to show the frequencies of strong winds of various durations and speeds from different directions. Details of some outstanding storms are given and estimates are made of probable extreme speeds for various averaging periods. The results, modified to represent conditions over the open sea, are used in conjunction with some well-known wave/wind relationships to provide estimates of wave-height frequencies for different direction ranges and of probable extreme wave heights in the Shetland area.

Introduction. Increasing mineral exploration in the northern North Sea in recent years with the discovery of some important oil fields to the east of the Shetland Islands has led to an increased demand from the offshore industry for detailed wind analyses for use in the design and operation of offshore structures. In order to answer such questions as 'how often is a wind of 40 kt or more likely to blow for 12 hours or more from a given direction?' or 'what is the wind speed averaged over 6 hours that is likely to be exceeded only once in 50 years?', it is essential to have a long series of continuous wind records in computer-accessible form. Such observational material is simply non-existent for the offshore sea areas, nor can it possibly be made available for at least another 10 years, by which time the need for it will probably have become less urgent.

However, we already have long-period continuous wind records for Lerwick Observatory and the data for the 14 years 1957–70 are available on magnetic tape. These data can be analysed to answer the sorts of question mentioned above and the results used to provide good estimates of wind conditions over the open sea in the general vicinity of the Shetland Islands, together with an indication of the wave conditions that they are likely to generate. Attention will be mainly confined to wind speeds averaging 25 kt or more and to durations of between 1 hour and 24 hours.

Frequencies of storms of various durations. Table I gives for each of the 12 30-degree direction ranges (350–010°, 020–040°, – – – – 320–340°) the numbers of spells of various durations during which successive hourly mean speeds were 25 kt or more, 30 kt or more and so on. The first part (350–010°) shows, for example, that there were six occasions during the 14 years when for

spells of 9 to 11 hours all hourly mean speeds were 30 kt or more from a direction in the range 350–010°. It should be noted that the frequencies are non-cumulative with respect to duration, i.e. a spell of, say, 12 hours with speeds of 30 kt or more is counted only once, in the column headed 12–14 hours, and is not also counted as two six-hour spells, four three-hour spells and so on. Hence, addition of the number in column 1, three times the number in column 2, six times the number in column 3, and so on, will approximately give the total number of hours with speeds equal to or greater than the speed concerned. However, exact total hours are given in the final column of each table. Incidentally, if these values are divided by the total numbers of spells given in the previous column, average spell-lengths for each speed level and direction are obtained and it is of some interest that these tended to be longest for wind directions from between 110 and 190° and to decrease in length with increasing speed.

An important conclusion from Table I is that the most severe storms (mean speeds of 55 kt or more throughout) came from directions between 200 and 280°. However, if attention is confined to storms having durations of three hours or more and mean speeds of 40 kt or more, that is to say, to storms which are likely to produce significant wave heights of over 5 metres, assuming that fetches are not limiting, their distribution with wind direction was as follows:

Direction range	Number of storms	Direction range	Number of storms
350–010°	3	170–190°	7
020–040°	3	200–220°	6
050–070°	0	230–250°	21
080–100°	0	260–280°	13
110–130°	0	290–310°	3
140–160°	6	320–340°	2
		Total	64

Clearly, storms which are of sufficient intensity and duration to produce high waves may come from a wide range of directions in the Shetland area. However, more than half of them came from between 230 and 280°,while directions between 050 and 130° produced none and so seem unlikely to develop very big seas. The anemograph at Lerwick has a good open exposure in all directions. The only shelter from easterly winds is provided by the small island of Bressay, bearing about 030 to 110°, rising to a height of about 225 m at a distance of about $5\frac{1}{2}$ km. Its effect is not likely to be very great as its terrain is relatively smooth and treeless.

In the original computer tabulations, frequencies were included for every duration, at 1-hour intervals, from 1 to 35 hours and for the ranges 36–41, 42–47, 48–59, 60–71 and 72 hours or more. They were given separately for the periods April to September and October to March as well as for the year as a whole. To give an indication of the seasonal variation the total frequencies for all directions are given in Table II for 'summer' (April–Sept.), 'winter' (Oct.–March) and for the whole year. Although the winter half-year accounts for a large majority of the storms, over 70 per cent in most categories, the summer half-year does experience an appreciable number with mean speeds of 40 kt or more lasting for several hours. However, every one of the 13 storms with mean speeds of 45 kt or more throughout, which occurred in the summer half-year took place either in

April or in September, there being none at all during the months May to August over the 14-year period. This is shown in Table III which gives the monthly distributions of the number of hours with mean speeds of 25, 30, 35, 40, 45, 50, 55 and 60 kt or more, irrespective of direction. It may also be seen that over the 14 years there were only 14 hours, one per year on the average, having mean speeds of 40 kt or more during the four months May to August, compared with 491 such hours in the other eight months of the year.

TABLE I—FREQUENCY OF SPELLS OF DURATIONS FROM 1 HOUR TO 24 HOURS OR MORE WITH HOURLY MEAN WIND SPEEDS EQUAL TO OR GREATER THAN THE STATED VALUES AND WITH MEAN WIND DIRECTIONS WITHIN THE STATED 30-DEGREE RANGES AT LERWICK (NUMBERS OF OCCURRENCES IN THE 14 YEARS 1957–70)

Speed (kt) ≥	Duration (hours) 1,2	3–5	6–8	9–11	12–14	15–17	18–23	≥24	Totals Spells	Totals Hours
	Numbers of occurrences									
					350–010°					
25	129	53	16	11	5	1	3	1	219	753
30	55	20	6	6	1			1	89	282
35	14	7	2					1	24	82
40	7	2					1		10	34
45	1			1					2	11
50	2	1							3	6
					020–040°					
25	105	51	17	9	3	4	2	1	192	697
30	53	22	7	1	2	2	1		88	283
35	29	13	1	1					44	106
40	12	3							15	23
45	2								2	2
					050–070°					
25	41	14	13	1	4			1	74	288
30	17	13	6					1	37	135
35	9	4	2		1				16	51
40	7								7	10
45	1								1	1
					080–100°					
25	35	15	6	2	3	2	1		64	262
30	16	8	1	1	1		1		28	105
35	4	2				1			7	31
40	2								2	2
					110–130°					
25	76	34	17	7	6	1	2	6	149	743
30	40	25	5	3	2	1	1		77	273
35	9	1	1		1				12	38
40	2								2	4
					140–160°					
25	142	74	25	13	7	3	4	15	283	1489
30	59	32	12	6	4	3	3	4	123	640
35	19	10	5		1	1	3		39	185
40	7	6							13	32
45	3								3	3
					170–190°					
25	149	76	35	26	10	9	8	6	319	1643
30	73	41	21	12	5	1	4	1	158	720
35	28	13	9	3					53	180
40	8	2	4	1					15	54
45	4	2	1						7	19

TABLE I—*continued*

Speed (kt) ≥	Duration (hours) 1,2	3–5	6–8	9–11	12–14	15–17	18–23	≥24	Totals Spells	Hours
	Numbers of occurrences									
						200–220°				
25	321	131	53	14	11	4	2	1	537	1686
30	165	68	13	4	3	2	1		256	698
35	66	20	3	2	2				93	223
40	32	6							38	65
45	5	2							7	14
50	4								4	6
55	2								2	3
60	1								1	1
						230–250°				
25	408	182	79	33	17	8	5	3	735	2604
30	217	98	34	13	5	1	2		370	1120
35	87	33	11	7		1			139	390
40	37	14	7						58	150
45	9	3	2						14	39
50	3	2							5	12
55	4								4	6
60	1								1	2
						260–280°				
25	285	103	48	17	15	6	3	1	478	1616
30	122	47	31	5	6	2			213	686
35	42	24	10	5					81	259
40	21	9	3	1					34	94
45	11	1	1						13	27
50	4		1						5	11
55	1	1							2	4
60	1								1	1
						290–310°				
25	117	43	14	9	6	2			191	610
30	47	24	8	6	1				86	271
35	25	5	2	1					33	79
40	5	2	1						8	22
45	1	1							2	4
50	2								2	3
						320–340°				
25	105	43	19	9	3		2	1	182	620
30	37	21	4	2	1		1		66	214
35	18	6		1					25	54
40	5	1	1						7	15
45	3								3	3
50	1								1	1

Details of some outstanding storms. Questions are raised from time to time about the profiles or structure of typical wind storms; for example, how long do they last, how quickly are their maximum speeds attained, how soon do they die away and is there a typical storm profile which could be assumed for engineering purposes.

In Figure 1 the hourly mean speeds and directions in each of the 15 storms in which speeds reached or exceeded 50 kt at Lerwick during the 14 years 1957–70 are plotted against time. All hours in which mean speeds were 30 kt or more are included, that is to say, 30 kt is taken as the threshold speed defining the beginning and end of each storm. This is a quite arbitrary rule, but some such rule is necessary as a basis for answering the questions mentioned in the preceding paragraph. On this basis the durations of the storms averaged about 17 hours,

ranging from 6 hours (number 7) to 37 hours (number 6). If the threshold speed had been set at only 25 kt the durations would have averaged about 25 hours, ranging from 15 hours (number 1) to 54 hours (number 2). It can be seen that if the threshold speed had been 40 kt then durations would have ranged from only 2 hours (number 13) to 21 hours (number 6). In some of the storms the maximum speed was reached in a few hours, for example in numbers 7, 10 and 13, but in others much more slowly, for example numbers 3 and 6. The rates of decline were also very variable. In only one of the 15 storms (number 6) did the wind direction back with time; in all the others it veered, sometimes gradually, sometimes more sharply. The total direction change, for a 30-knot threshold speed, ranged from about 20 degrees to about 100 degrees.

There is an apparent discrepancy between the 15 storms of Figure 1 and the 20 spells with hourly mean speeds of 50 kt or more shown by Table II. The explanation lies in the fact that some of the storms of Figure 1 include more than one of the spells listed in Table II, which represent all occasions of one hour or more with speeds of 50 kt or more from within one of the 12 fixed 30-degree direction ranges. Thus storm number 3 (Figure 1) includes a one-hour spell from 200–220° and a two-hour spell from 230–250° while storm number 6 includes one three-hour and one two-hour spell, each from 350–010° but separated by an hour with mean speed below 50 kt.

The storms whose profiles are shown in Figure 1 were selected on the basis of a high maximum speed, irrespective of wind direction. Some of these may not

TABLE II—FREQUENCIES OF SPELLS OF DURATIONS FROM 1 HOUR TO 24 HOURS OR MORE WITH HOURLY MEAN WIND SPEEDS EQUAL TO OR GREATER THAN THE STATED VALUES AND FOR ALL DIRECTION RANGES COMBINED AT LERWICK (NUMBERS OF OCCURRENCES IN THE 14 YEARS 1957–70 FOR SUMMER (APRIL–SEPTEMBER), WINTER (OCTOBER–MARCH) AND YEAR)

		Duration (hours)								Totals	
Speed (kt) ≥		1,2	3–5	6–8	9–11	12–14	15–17	18–23	≥24	Spells	Hours
Summer	25	515	218	74	33	25	8	5	4	882	2 992
	30	168	90	26	12	5	1	2	1	305	997
	35	63	22	5	5		1			96	260
	40	22	6	3	1					32	84
	45	10	2	1						13	27
	50	4		1						5	12
	55	1	1							2	4
Winter	25	1398	601	268	118	65	32	27	32	2541	10 019
	30	733	329	122	47	26	11	12	6	1286	4 430
	35	287	116	41	15	5	2	3	1	470	1 418
	40	123	39	13	1			1		177	421
	45	30	7	3	1					41	96
	50	12	3							15	27
	55	6								6	9
	60	3								3	4
Year	25	1913	819	342	151	90	40	32	36	3423	13 011
	30	901	419	148	59	31	12	14	7	1591	5 427
	35	350	138	46	20	5	3	3	1	566	1 678
	40	145	45	16	2			1		209	505
	45	40	9	4	1					54	123
	50	16	3	1						20	39
	55	7	1							8	13
	60	3								3	4

TABLE III—TOTAL NUMBERS OF HOURS WITH MEAN WIND SPEEDS EQUAL TO OR GREATER THAN STATED VALUES IN EACH MONTH DURING THE 14 YEARS 1957–70 AT LERWICK, IRRESPECTIVE OF DIRECTION

	Mean speed equal to or greater than							
	25 kt	30 kt	35 kt	40 kt	45 kt	50 kt	55 kt	60 kt
	Numbers of hours							
January	1 981	919	317	109	26	8	5	4
February	1 464	642	201	89	29	5	2	
March	1 998	949	210	40	8	3		
April	799	295	89	25	7	2	1	
May	445	173	46	10				
June	584	154	7					
July	259	41	11					
August	265	71	20	4				
September	640	263	87	45	20	10	3	
October	1 309	522	184	66	22	9	2	
November	1 302	422	120	29	2			
December	1 965	976	386	88	9	2		
Year	13 011	5427	1678	505	123	39	13	4

have been very effective in generating high waves either because the higher speeds were of limited duration or because there were marked changes in wind direction. An alternative selection of notable storms could be made on the basis of a high average speed over a longer period, say 40 kt or more over 12 hours, combined with a limited direction range, say 40 degrees or less. There were 13 storms which met these criteria, seven of which already appear in Figure 1 (numbers 2, 3, 6, 8, 10, 11 and 12) and the other six of which are shown in Figure 2. In both figures a horizontal line drawn beneath each relevant speed profile shows the 12-hour period giving the highest average speed, and is labelled to show the average speed and direction range concerned.

Like the 15 storms of Figure 1, these 13 12-hour storms have no common feature, although the majority of the speed profiles show an increase followed by a decrease, and the majority of the direction profiles show a more or less steady veer with time. Thus it cannot be said that there is a typical storm profile.

Extreme wind speeds. Table IV shows the highest mean wind speeds, reduced to the standard height of 10 m, recorded in each of the years 1957 to 1970 for durations ranging from 1 hour to 72 hours and for direction ranges of 40 degrees or less. In any one year the highest speeds are given for each duration irrespective of the storm in which they occurred, but as the times and dates of commencement are given it can easily be seen which spells occurred in the same storm. Out of the 14 years there were 9 in which hourly mean speeds of 50 kt or more occurred, the highest speed being 63 kt in January 1961. Nine years also produced 6-hour mean speeds of 45 kt or more, seven years gave 12-hour means of 40 kt or more while 11 years gave 24-hour means of 35 kt or more. Even over as long a period as 48 hours, eight of the 14 years gave mean speeds of 30 kt or more.

Tables V and VI give the annual extreme speeds over 12-hour and 24-hour periods respectively, together with the highest speeds averaged over shorter periods in the same storms. As in Table IV the speeds were reduced to the standard height of 10 m and are for direction ranges of 40 degrees or less.

TABLE IV—HIGHEST MEAN WIND SPEEDS IN KNOTS OVER STATED DURATIONS IN EACH OF THE YEARS 1957 TO 1970 AT LERWICK, WITH TIMES OF COMMENCEMENT (GMT); DIRECTION RANGES ARE RESTRICTED TO 40° FOR DURATIONS OF 3 HOURS OR MORE, AND SPEEDS ARE REDUCED TO THE VALUES APPROPRIATE TO A HEIGHT OF 10 METRES

	Duration (hours)								
	1	3	6	12	18	24	36	48	72
1957	54 11h 5 Feb	51·9 11h 5 Feb	49·2 11h 5 Feb	44·0 11h 5 Feb	36·9 19h 19 Jan	36·7 22h 7 Jan	35·3 13h 7 Jan	27·6 12h 13 Sept	20·6 4h 17 Nov
1958	52 18h 18 Jan	46·5 17h 18 Jan	40·3 2h 29 Dec	39·4 1h 29 Dec	37·5 21h 28 Dec	35·9 21h 28 Dec	33·1 8h 12 Dec	30·0 13h 28 Dec	23·9 19h 25 Jan
1959	49 4h 28 Oct	49·3 23h 27 Oct	49·1 23h 27 Oct	46·5 20h 27 Oct	44·8 13h 27 Oct	43·4 9h 27 Oct	40·3 8h 27 Oct	36·7 8h 6 Dec	29·9 17h 9 Mar
1960	50 4h 14 Apr	46·6 3h 14 Apr	40·6 6h 5 Apr	38·9 0h 5 Apr	37·9 18h 4 Apr	37·0 13h 4 Apr	35·0 1h 4 Apr	32·4 17h 19 Mar	31·2 21h 18 Mar
1961	63 20h 27 Jan	62·7 18h 27 Jan	49·1 13h 27 Jan	42·9 7h 27 Jan	39·8 1h 27 Jan	41·0 19h 26 Jan	38·6 7h 26 Jan	30·0 18h 17 Jan	27·4 0h 17 Jan
1962	44 3h 16 Feb	44·0 21h 11 Jan	42·2 0h 16 Feb	39·3 19h 15 Feb	36·1 16h 15 Feb	33·5 10h 15 Feb	29·4 7h 9 Jan	21·8 5h 29 Jan	18·6 10h 23 May
1963	58 17h 26 Sept	56·0 16h 26 Sept	54·5 15h 26 Sept	46·8 14h 26 Sept	37·2 21h 24 Dec	36·6 15h 24 Dec	36·8 3h 24 Dec	30·7 18h 22 Dec	23·8 18h 26 Jun
1964	47 11h 12 Dec	45·3 10h 12 Dec	42·8 10h 12 Dec	39·7 13h 14 Mar	38·7 10h 14 Mar	37·7 9h 14 Mar	36·3 23h 13 Mar	35·4 13h 13 Mar	33·0 2h 13 Mar
1965	58 20h 28 Oct	55·0 19h 28 Oct	52·2 17h 28 Oct	46·8 14h 28 Oct	36·3 22h 30 Oct	32·8 18h 30 Oct	27·1 5h 13 Feb	24·1 5h 13 Feb	22·6 17h 7 Apr
1966	52 16h 23 Dec	47·7 13h 6 Sept	47·0 13h 6 Sept	44·8 11h 6 Sept	38·2 15h 6 Sept	36·0 15h 6 Sept	32·1 15h 6 Sept	29·8 15h 6 Sept	24·4 5h 8 Jan
1967	53 15h 6 Mar	51·7 14h 6 Mar	48·8 12h 6 Mar	39·5 4h 3 Dec	37·4 9h 21 Mar	35·6 5h 21 Mar	31·8 0h 21 Mar	30·8 10h 20 Mar	27·3 1h 15 Feb
1968	47 13h 4 Feb	47·0 11h 4 Feb	46·2 10h 4 Feb	44·7 8h 4 Feb	42·3 5h 4 Feb	37·7 3h 4 Feb	31·0 13h 2 Apr	27·1 12h 30 Oct	25·7 16h 12 Nov
1969	50 23h 28 Sept	48·7 22h 28 Sept	45·5 21h 28 Sept	39·1 21h 28 Sept	37·9 8h 14 Dec	37·1 2h 14 Dec	35·6 16h 13 Dec	34·4 11h 13 Dec	30·6 19h 14 Mar
1970	42 1h 24 Apr	41·3 0h 24 Apr	40·5 22h 23 Apr	37·8 21h 23 Apr	35·2 20h 23 Apr	32·7 19h 23 Apr	28·9 5h 19 Oct	27·4 2h 21 Jan	24·9 2h 21 Jan
All years	63 20h 27/1/61	62·7 18h 27/1/61	54·5 15h 26/9/63	46·8 14h 26/9/63	44·8 13h 27/10/59	43·4 9h 27/10/59	40·3 8h 27/10/59	36·7 8h 6/12/59	33·0 2h 13/3/64

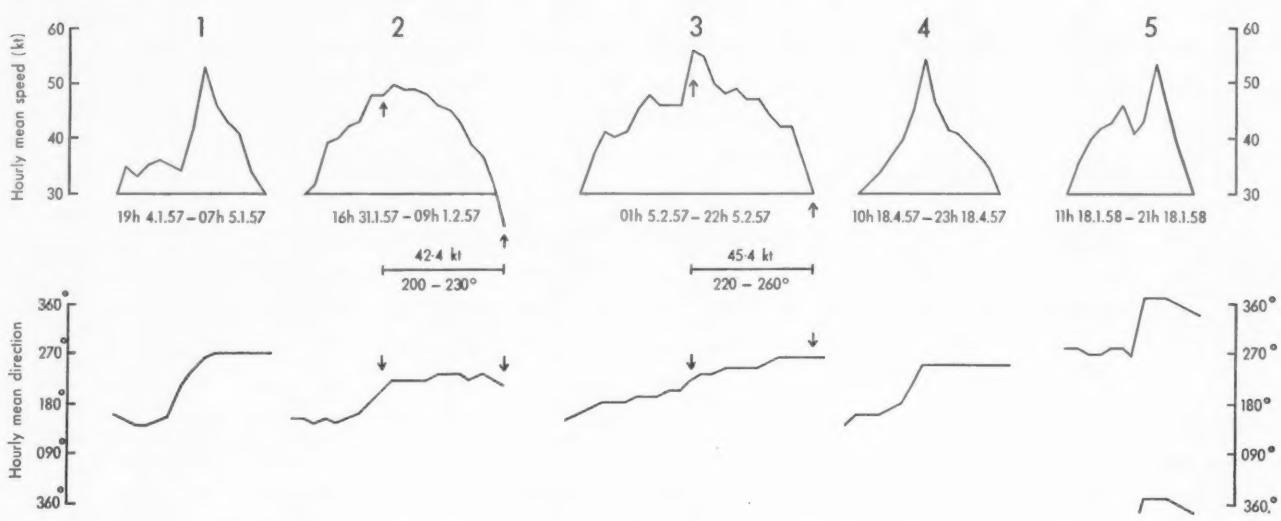

FIGURE 1 — PROFILES OF 15 STORMS IN WHICH AN HOURLY MEAN SPEED OF 50 KNOTS OR MORE WAS RECORDED AT LERWICK DURING THE PERIOD 1957–70 INCLUSIVE

Storms numbered 2 and 3 include 12-hour periods with average speeds of 40 kt or more and direction ranges of 40° or less.

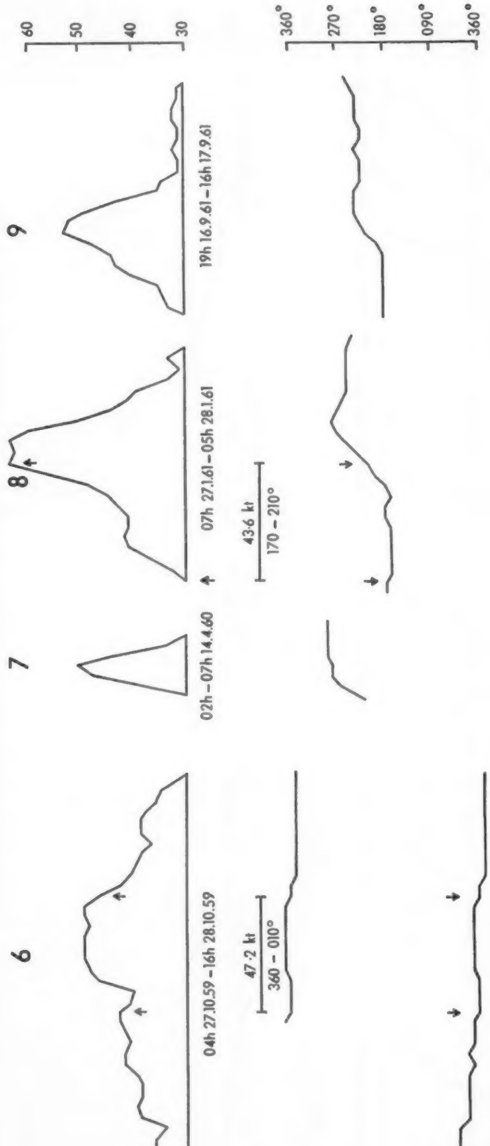

FIGURE 1—*continued*
Storms numbered 6 and 8 include 12-hour periods with average speeds of 40 kt or more and direction ranges of 40° or less.

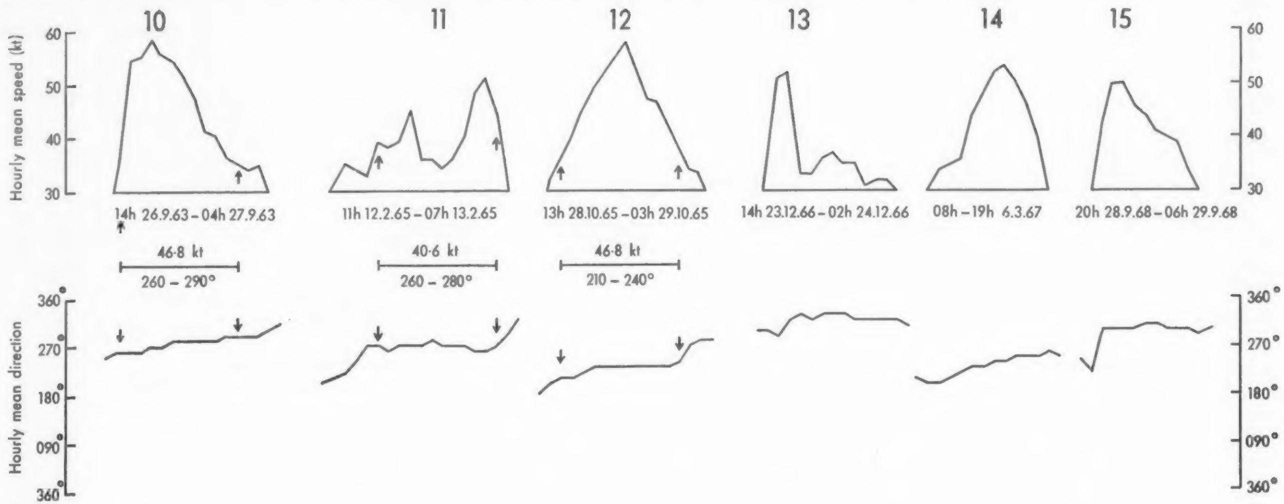

FIGURE 1—*continued*

Storms numbered 10, 11 and 12 include 12-hour periods with average speeds of 40 kt or more and direction ranges of 40° or less.

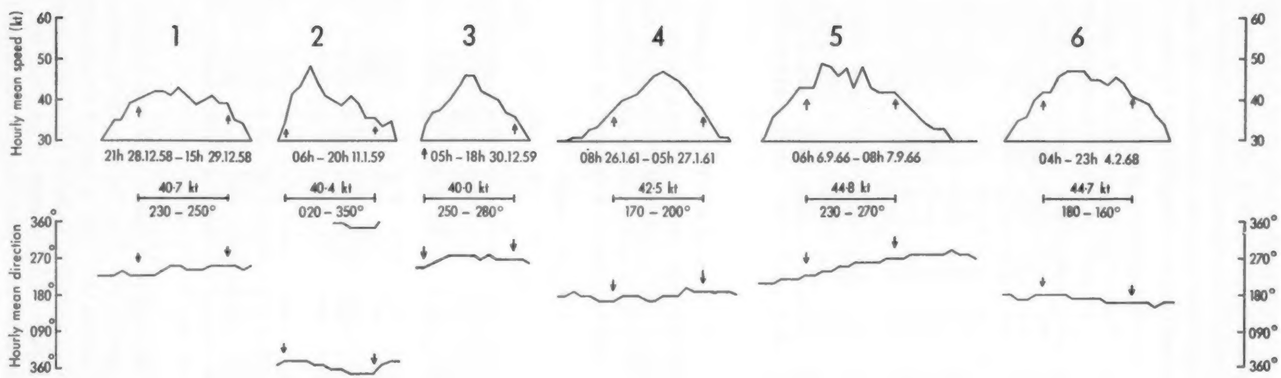

FIGURE 2—PROFILES OF SIX ADDITIONAL STORMS IN WHICH THERE WERE 12-HOUR PERIODS WITH AVERAGE SPEEDS OF 40 KNOTS OR MORE AND DIRECTION RANGES OF 40 DEGREES OR LESS AT LERWICK DURING THE PERIOD 1957–70 INCLUSIVE

TABLE V—HIGHEST MEAN WIND SPEED IN KNOTS OVER A 12-HOUR PERIOD DURING WHICH THE DIRECTION RANGE DID NOT EXCEED 40° IN EACH OF THE YEARS 1957 TO 1970 AT LERWICK, TOGETHER WITH MAXIMUM SPEEDS OVER PERIODS OF 1 HOUR AND 3, 6, AND 9 HOURS IN THE SAME STORMS; ALL SPEEDS ARE REDUCED TO VALUES APPROPRIATE TO A HEIGHT OF 10 METRES

	Duration (hours)					
	1	3	6 *knots*	9	12	Times of commencement
1957	54	51·9	49·2	47·1	44·0	11h 5 Feb.
1958	42	40·6	40·3	39·8	39·4	1h 29 Dec.
1959	49	49·3	49·1	48·4	46·5	20h 27 Oct.
1960	44	42·4	40·6	39·5	38·9	0h 5 Apr.
1961	63	55·8	49·1	46·3	42·9	7h 27 Jan.
1962	44	43·3	42·2	40·8	39·3	19h 15 Feb.
1963	58	56·0	54·5	50·6	46·8	14h 26 Sept.
1964	42	41·3	40·7	40·2	39·7	12h 14 Mar.
1965	58	55·0	52·2	49·7	46·8	14h 28 Oct.
1966	49	47·7	47·0	45·7	44·8	11h 6 Sept.
1967	42	41·0	40·7	40·1	39·5	4h 3 Dec.
1968	47	47·0	46·2	45·7	44·7	8h 4 Feb.
1969	50	48·7	45·5	42·9	39·1	21h 28 Sept.
1970	42	41·3	40·5	39·1	37·8	21h 23 Apr.

TABLE VI—HIGHEST MEAN WIND SPEED IN KNOTS OVER A 24-HOUR PERIOD DURING WHICH THE DIRECTION RANGE DID NOT EXCEED 40° IN EACH OF THE YEARS 1957 TO 1970 AT LERWICK, TOGETHER WITH MAXIMUM SPEEDS OVER PERIODS OF 1 HOUR AND 3, 6, 9, 12, 15 AND 18 HOURS IN THE SAME STORM; ALL SPEEDS ARE REDUCED TO VALUES APPROPRIATE TO A HEIGHT OF 10 METRES

	Duration (hours)								
	1	3	6	9	12 *knots*	15	18	24	Times of commencement
1957	41	39·4	38·6	38·5	38·1	37·0	36·3	36·7	20h 7 Jan.
1958	42	40·6	40·3	39·8	39·4	38·5	37·5	35·9	21h 28 Dec.
1959	49	49·3	49·1	48·4	46·5	45·6	44·8	43·4	9h 27 Oct.
1960	44	42·4	40·6	39·5	38·9	38·2	37·9	37·0	13h 4 Apr.
1961	63	55·8	49·1	46·3	42·9	40·3	39·8	41·0	19h 26 Jan.
1962	44	43·3	42·2	40·8	39·3	37·9	36·1	33·5	10h 15 Feb.
1963	46	45·0	43·0	41·2	39·8	38·3	37·2	36·6	15h 24 Dec.
1964	42	41·3	40·7	40·2	39·7	39·2	38·7	37·7	9h 14 Mar.
1965	47	44·3	41·5	40·6	38·8	37·5	36·3	32·8	18h 30 Oct.
1966	48	46·3	45·0	43·8	41·8	39·9	38·2	36·0	15h 6 Sept.
1967	47	45·0	42·5	40·9	39·1	37·7	37·4	35·6	5h 21 Mar.
1968	47	47·0	46·2	45·7	44·7	43·7	42·3	37·7	3h 4 Feb.
1969	40	39·3	39·0	38·9	38·6	38·3	37·9	37·1	2h 14 Dec.
1970	42	41·3	40·5	39·1	37·8	36·9	35·2	32·7	19h 23 Apr.

Amongst other things the data in Tables IV, V and VI may be used to estimate how extreme wind speeds fall off as the averaging period is increased beyond one hour. Average speeds over the 14 years for each duration were computed from each table and expressed as ratios of the averages over one hour, and the results are given in Table VII. As was to be expected, the mean ratios derived from the same storms for each year, that is to say from Tables V and VI,

are somewhat higher than those based on the highest speeds irrespective of the storms in which they occurred, as given in Table IV, particuarly for the longer averaging periods. It is suggested that the ratios in line (a) of Table VII should be used when, given an extreme hourly mean speed such as might be computed from anemograph records or interpolated from a map of once-in-50-year hourly mean speeds, it is desired to estimate an extreme for a longer period, say 24 hours, having the same probability, it being understood of course that the longer period is one in which wind direction remains within a 40-degree range. Thus if the once-in-50-year hourly mean speed was 65 kt then the estimated once-in-50-year 12-hour and 24-hour means would be about $65 \times 0{\cdot}82 = 53$ kt and $65 \times 0{\cdot}71 = 46$ kt respectively. The ratios on lines (b) and (c) of Table VII on the other hand might be used when, given an extreme for one averaging period, it was desired to estimate probable extremes for other, longer or shorter, averaging periods in the same storm. Thus, given a highest 24-hour mean of 45 kt in a storm with no great direction change the probable highest 3-hour mean in the same storm would be about $45 \times 0{\cdot}97/0{\cdot}80 = 55$ kt; or given a highest hourly mean of 60 kt the probable 12-hour extreme in the same storm, assuming no great direction change, would be about $60 \times 0{\cdot}86 = 52$ kt. Also shown on line (d) of Table VII are ratios previously estimated by Shellard and published by the Department of Energy,[1] which are in very good agreement with those now derived from 24-hour storms at Lerwick.

TABLE VII—RATIOS OF MAXIMUM SPEEDS AVERAGED OVER VARYING NUMBERS OF HOURS (V_t) TO MAXIMUM SPEEDS OVER ONE HOUR (V_1) AT LERWICK

	Period t (hours)							
	3	6	12	18	24	36	48	72
	Ratio V_t/V_1							
(a)	0·96	0·90	0·82	0·74	0·71	0·66	0·58	0·51
(b)	0·97	0·93	0·86					
(c)	0·97	0·93	0·88	0·83	0·80			
(d)	0·96	0·93	0·87		0·80			

(a) derived from annual extremes for each duration irrespective of the storm in which they occurred;
(b) from maximum 12-hour storms;
(c) from maximum 24-hour storms;
(d) for comparison—values as given by Shellard in reference 1.

The annual extreme wind speeds presented in Tables IV, V and VI may be fitted by extreme-value distributions of the Gumbel type, so providing estimates of extreme wind speeds for different averaging periods (durations) likely to be exceeded on average only once in, say, 50 or 100 years. Such estimates have been computed for average recurrence periods of 10, 20, 50, 100 and 200 years and are presented in Table VIII. Those in part (a) of the table were derived from Table IV and once-in-50-year extremes range from 71 kt for hourly means to 40 kt for 72-hour means. Those in parts (b) and (c) were derived from Tables V and VI and give for the same recurrence periods the probable extreme speeds in 12-hour and 24-hour storms respectively. In all cases direction ranges are assumed to be 40 degrees or less.

TABLE VIII—ESTIMATED EXTREME WIND SPEEDS AT LERWICK FOR VARIOUS DURATIONS AND AVERAGE RECURRENCE PERIODS

(a) Estimated from data in Table IV, i.e. from highest speeds irrespective of the storms in which they occurred.

Average recurrence period	Duration (hours) 1	3	6	12	18	24	36	48	72
	Extreme wind speed in knots for durations shown								
10 years	61	59	54	48	43	42	40	37	33
20 years	65	63	57	50	45	44	43	40	36
50 years	71	68	61	53	47	46	47	44	40
100 years	75	72	65	56	49	48	49	47	43
200 years	79	76	68	58	50	50	52	49	46

(b) Estimated from data in Table V, i.e. from highest speeds in maximum 12-hour storms.

Average recurrence period	Duration (hours) 1	3	6	9	12
	Extreme wind speed in knots for durations shown				
10 years	61	57	54	51	48
20 years	66	61	57	54	50
50 years	72	67	62	58	53
100 years	77	71	65	61	56
200 years	82	75	68	63	58

(c) Estimated from data in Table VI, i.e. from highest speeds in maximum 24-hour storms.

Average recurrence period	Duration (hours) 1	3	6	9	12	15	18	24
	Extreme wind speed in knots for durations shown							
10 years	56	52	49	47	45	44	43	42
20 years	60	55	51	49	47	45	45	44
50 years	65	59	54	52	49	48	47	46
100 years	69	62	57	54	51	49	49	48
200 years	73	65	59	56	53	51	51	50

Application to wave prediction. As mentioned earlier, the original computer tabulations gave for each 30-degree direction range the numbers of spells with speeds equal to or greater than 20, 25, 30 etc. kt, and with durations of 1, 2, 3, . . . 35 hours and 36 hours or more. By employing the wave-prediction technique of Darbyshire and Draper,[2] modified by Draper,[3] these frequencies may be converted into wave-height frequencies. The relationship is not a simple one since wave height depends on both wind speed and duration, but the procedure used is illustrated in Table IX. In this table the numbers of 3-hour spells with speeds exceeding the values in column 1 and with directions in the range 230–250° is given in column 2. In column 3 the speeds of column 1 were adjusted to represent more closely the probable mean speeds over the open sea rather than those measured at Lerwick itself. The correction applied was a straightforward increase of 10 per cent, which figure was arrived at as follows. At coastal anemograph stations and in strong winds the average ratio of the

maximum gust speed to the maximum hourly mean speed, G (3-s, 60-min) has been shown by Shellard[4] to be about 1·5. Measurements over the sea by Goptarev,[5] Dorrestein[6] and Walden[7] suggest that G (3-s, 10-min) is no more than 1·3 and this corresponds to a value of G (3-s, 60-min) of about 1·37. Also recent measurements on fixed gas-production platforms in the southern North Sea have shown G (3-s, 60-min) to be about 1·2 for anemographs at a height of 80 m or so. When speeds are reduced to the standard height of 10 m using appropriate power-law formulae (exponent 0·12 for hourly means and 0·06 for gusts) this too gives a ratio of about 1·37. On the assumption that in strong winds maximum gust speeds will be much the same over the open sea as they are on nearby coasts, both being mainly dependent on the gradient wind speed, maximum hourly mean speeds over the sea will be about 1·50/1·37 or about 1·10 times those on nearby coasts.

Next it was necessary to decide which set of wave-prediction graphs provided by Darbyshire and Draper should be used, those for oceanic waters or those for coastal waters. On the advice of one of the authors (L. Draper, personal communication) the oceanic-waters graphs were used as being more appropriate to the Shetland area. It should be mentioned that the oceanic-waters graphs were derived from measurements made at the ocean weather stations 'I' and 'J', that is to say from wind speeds measured over the open sea. Had the coastal-waters graphs been used it would have been more correct to use the wind speeds as measured at Lerwick because these graphs were based on wind measurements made at coastal stations. The wave-prediction graphs provide estimates of (a) maximum wave height in feet during a 10-minute period and (b) significant wave period in seconds, for various combinations of wind speed and duration (or fetch). The appropriate values of these items are given in columns 4 and 5 of Table IX, wave heights being converted to metres. Columns 6 and 7 give the numbers of waves in the storm (in this case in three hours) and in the 10-minute period respectively, and column 8 gives the corresponding wave-height factors F_2 and F_1, obtained from a diagram given by Draper (Figure 2 of reference 3) and their ratio. This diagram gives the ratio of maximum wave height to root-mean-square wave height for various numbers of waves. Since this ratio increases with number of waves, the ratio F_2/F_1 represents the greater chance of a number of component waves getting into phase during the whole storm than in the 10-minute recording period on which the wave-prediction graphs are based; thus the last column of Table IX gives values of H_{max} (10-min) $\times$ F_2/F_1, the estimated maximum wave height in the storm.

Hence, from each set of wind-speed frequencies, one for each direction range and duration, a set of highest-wave-in-storm frequencies can be obtained. These frequencies, derived from storms of various durations, can then be combined to give overall frequencies of waves exceeding various heights from each direction. This was done by plotting each set of frequencies against wave heights, for example column 2 against column 9 of Table IX, on log-linear graph paper and then reading off, by interpolation, the frequencies of wave heights at intervals of $1\frac{1}{2}$ metres from $4\frac{1}{2}$ metres upwards. These were then summed to give the results presented in Table X.

In the process of deriving Table X some information was obtained which related highest storm waves to storm duration. This is summarized in Table XI which gives numbers of storms in which the predicted highest wave exceeded stated heights, arranged according to storm duration, all wind directions being

TABLE IX—EXAMPLE OF THE APPLICATION OF THE DARBYSHIRE–DRAPER WAVE-PREDICTION TECHNIQUE TO THE 3-HOUR STORM FREQUENCIES FOR THE 230–250° DIRECTION RANGE AT LERWICK, 1957–70

Mean wind speed equal to or greater than	Number of 3-hour storms from 230–250°	Estimated wind speed over open sea equal to or greater than	Maximum wave height H_{max} (10-min) equal to or greater than	Significant wave period	Number of waves in storm	Number of waves in 10 minutes	Ratio of wave-height factors* F_2/F_1	Highest wave in storm equal to or greater than
kt		*kt*	*m*	*s*				*m*
20	127	22	1·4	5·8	1860	103	1·28	1·8
25	87	27·5	2·7	6·8	1590	88	1·28	3·5
30	57	33	4·0	8·2	1320	73	1·29	5·2
35	17	38·5	5·8	9·1	1190	66	1·29	7·5
40	8	44	8·1	10·3	1050	58	1·29	11·3
45	1	49·5	10·5	11·4	950	53	1·30	13·6
50	1	55	13·4	12·8	840	47	1·31	17·5

* See page 203 for explanation of these factors.

TABLE X—NUMBERS OF STORMS IN 14 YEARS (1957–70) OVER THE SHETLAND ISLANDS IN WHICH THE HEIGHT OF THE PREDICTED HIGHEST WAVE WAS $4\frac{1}{2}$ METRES OR MORE, ARRANGED ACCORDING TO WAVE HEIGHT AND WIND DIRECTION

Wave height *metres*	Direction range (degrees)												
	350–010	020–040	050–070	080–100	110–130	140–160	170–190	200–220	230–250	260–280	290–310	320–340	Totals
$4\frac{1}{2}$ or more	95	94	37	28	87	151	191	239	372	206	82	79	1661
6 or more	48	46	23	14	45	84	119	130	195	124	45	41	914
$7\frac{1}{2}$ or more	27	27	13	6	17	51	68	60	115	80	24	20	508
9 or more	14	14	6	2	5	30	35	24	67	48	12	7	264
$10\frac{1}{2}$ or more	8	5	1		2	15	17	12	38	29	6	3	136
12 or more	6	1				8	10	6	21	14	3	1	70
$13\frac{1}{2}$ or more	4					1	7	5	12	7	3	1	40
15 or more	3						2	2	8	3			18
$16\frac{1}{2}$ or more	2						1	1	7	3			14
18 or more	1								2	2			5
$19\frac{1}{2}$ or more									1	2			3
21 or more									1	2			3
$22\frac{1}{2}$ or more										1			1

combined. It will be seen that all but one of the 18 storms in which the predicted highest wave was 15 m or more in height had durations of less than 10 hours, that all five storms in which the predicted highest wave was 18 m or more in height had durations of less than 10 hours and that all three storms in which the predicted highest wave was 21 m or more in height had durations of between 2 and 6 hours. It appears that in the Shetland area the highest waves tend to be associated with rather severe gales of relatively short duration. Over the 14-year period there were only two storms having a duration of 24 hours or more and giving predicted highest waves of 10½ m or more and only one storm of duration 36 hours or more giving a predicted highest wave of 9 m or more.

It should be noted that the predicted wave heights given in Tables X and XI take no account of swell. However, according to an analysis of wave data for ocean weather station 'I' (59°N, 19°W) by Hogben[8] the mean underlying swell in that area of the North Atlantic has a height of about 2 metres. The addition of an average swell wave of 2 m to wind waves of 6 m, 12 m and 24 m would give resultant waves of only 6·3, 12·2 and 24·1 m respectively. Even an exceptionally heavy swell of, say, 6 m when combined with sea waves of 12 and 24 m would give resultant waves of only 13·4 and 24·7 m respectively.

Returning to Table X, it should be stressed that too much significance should not be attached to the actual frequencies given there, or in Table I, bearing in mind how they were obtained. Each 30-degree range was treated separately so that if, in a given storm, the wind direction veered or backed into an adjacent sector, that particular storm would have been terminated, even though the overall direction range may have been small enough for the storm to have been quite effective in developing waves. Also, the greater the duration of a storm the more likely would it be to be terminated in this way, thus being counted as two, or more, storms of lesser duration. However, the relative significance of the frequencies as given will not have been much affected by these occasional happenings and it is thought that the relative frequencies of waves of different heights from various directions are adequately represented by Table X.

The table shows that the three highest waves, those of 21 m or more in height, came from directions between 230 and 280°, whereas those of 15 m or more, averaging just over one per year, came either from between 170 and 280° or from 350–010°. Between the directions 050° and 130° waves of 12 m or more in height appear to be unlikely in the Shetland area.

Probable extreme wave heights. Finally, the Darbyshire/Draper wave-prediction technique may be applied to the extreme-wind-speed estimates given in Table VIII to provide estimates of the highest waves to be expected on average only once in 10, 20, 50, 100 or 200 years. This has been done for an average recurrence period of 50 years using the appropriate wind speeds taken from part (a) of Table VIII and the results are given in Table XII. The values of $H_{\max}$ (10-min) and of wave period enclosed in brackets are values whose derivation necessitated some limited extrapolation of the Darbyshire and Draper graphs. Since some preliminary calculations indicated that the predicted extreme wave heights increased rather quickly to a maximum value as the storm duration increased, interpolated extreme wind speeds for durations of 2, 4 and 5 hours were also used and the results are included in the table in view of the fact that the maximum value and the duration at which it occurs are of special interest.

TABLE XI—NUMBERS OF STORMS IN 14 YEARS (1957–71) IN WHICH THE HIGHEST WAVES IN THE WATERS AROUND THE SHETLAND ISLANDS ARE ESTIMATED TO HAVE EQUALLED OR EXCEEDED THE STATED HEIGHTS, ARRANGED ACCORDING TO STORM DURATION

Wave height *metres*	Storm duration (hours)																
	1	2	3	4	5	6	7	8	9	10	11–15	16–20	21–25	26–30	31–35	≥36	Totals
4½ or more	18	154	236	202	177	141	136	112	72	74	195	71	34	13	7	19	1661
6 or more	9	80	132	104	106	85	79	55	41	40	98	34	25	11	6	9	914
7½ or more	3	49	72	56	51	52	51	30	23	22	58	21	11	4	1	4	508
9 or more	3	24	36	31	22	30	26	14	13	12	25	13	10	3	1	1	264
10½ or more	2	14	24	15	11	13	16	8	9	6	11	5	2				136
12 or more		9	10	7	8	8	9	3	4	3	2	5	2				70
13½ or more		7	6	4	4	6	7	2	3			1					40
15 or more		3	3	3	1	3	3		1			1					18
16½ or more		3	3	1	1	3	2		1								14
18 or more		1	1	1		1			1								5
19½ or more		1	1			1											3
21 or more		1	1			1											3
22½ or more			1														1

TABLE XII—PREDICTED EXTREME WAVE HEIGHTS FOR STORMS HAVING AN AVERAGE RECURRENCE PERIOD OF 50 YEARS AND DIFFERENT DURATIONS IN THE SHETLAND AREA

Storm duration	Once in-50-year wind speed	Estimated wind speed over open sea	Maximum wave height H_{max} (10-min)	Significant wave period	Number of waves in storm	Number of waves in 10 minutes	Ratio of wave-height factors F_2/F_1	Highest wave in storm
hours	*kt*	*kt*	*m*	*s*				*m*
1	71	78	(17)	(15½)	232	39	1·20	20½
2	70	77	(24½)	(18½)	389	32½	1·28	31½
3	68	75	(26½)	(19½)	554	31	1·33	35
4	65½	72	(26)	(19)	758	31½	1·36	35½
5	63½	70	25½	18¾	964	32	1·38	35
6	61	67	24	18	1 200	33	1·40	33½
12	53	58½	19½	15½	2 787	39	1·45	28
18	47	51½	14½	13½	4 800	44	1·47	21½
24	46	50½	14½	13½	6 400	44	1·51	22
36	47	51½	(15)	(14)	9 257	43	1·53	23
48	44	48½	(13½)	(13)	13 292	46	1·55	21
72	40	44	(11½)	(12½)	20 736	48	1·58	18

Bracketed figures are extrapolated (see page 205).

The maximum once-in-50-year wave height of just over 35 m (about 115 ft) is associated with a once-in-50-year mean wind speed of 72 kt having a duration of about 4 hours. The corresponding significant wave period is about 19 seconds. This maximum wave height compares with a once-in-50-year value of between 30 and 33 m to the west of the Shetlands taken from the map of 50-year design wave heights prepared by Draper and published by the Department of Energy.[1] Considering the various uncertainties involved this may be regarded as a satisfactory degree of agreement.

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THE DISTRIBUTION OF RAINFALL OVER SUBCATCHMENTS OF THE RIVER DEE AS A FUNCTION OF SYNOPTIC TYPE

By C. A. NICHOLASS and T. W. HARROLD

Summary. Two years of data from a network of 63 tipping-bucket rain-gauges distributed over the 1000-km² catchment area of the upper portion of the River Dee have been analysed to derive relationships between the rainfall over subcatchments of area typically 60 km² (R_s) and that averaged over the entire area of the network (R). It is shown that the ratio R_s/R is dependent on the synoptic type and surface wind direction. Using these two parameters as inputs, the distribution of storm rainfall within the upper portion of the Dee Catchment could be forecast with adequate accuracy from an accurate quantitative forecast of the rainfall over the whole catchment area. The extent to which this conclusion can be applied to other areas is discussed.

Introduction. A network of 63 tipping-bucket rain-gauges is operated by the Water Data Unit and the Welsh National Water Development Authority as part of the Dee Weather Radar Project (see for example Harrold, English and Nicholass[1]). These gauges provide data in 15-minute time periods over a 1000-km² catchment area of the upper portion of the River Dee in North Wales.

Two years of the data obtained have been used to determine relationships between subcatchment and catchment areal rainfalls for different synoptic weather types. The subcatchments vary in size from 20 km² to 104 km² (see Figure 1).

Such relationships may be of use to the forecaster and hydrologist, since they would enable forecasts of rainfall amounts over large areas, such as those which will be available eventually from computer models, to be used in estimating rainfall over the much smaller areas which are of importance to hydrologists, particularly in the efficient operation of regulating reservoirs.

Although the data demonstrate only the relationships which exist within the Dee Catchment, ways in which similar climatological rules could be investigated in other river catchment areas are discussed.

Analysis and results. For the two-year period ending April 1974 the synoptic type and surface wind were classified by reference to the *Daily Weather Report*. The surface wind velocity over the Dee Catchment was estimated from

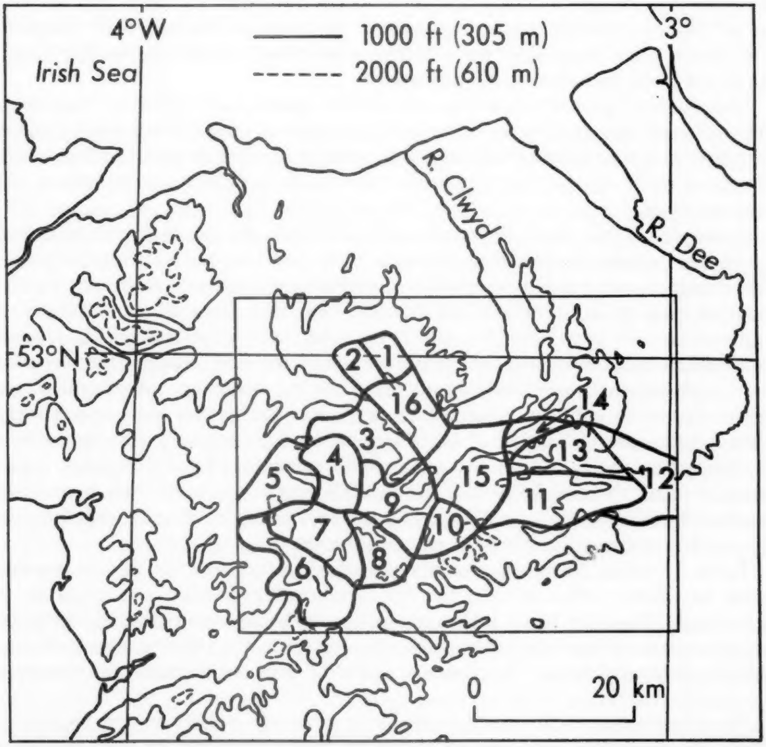

FIGURE 1—MAP SHOWING THE LOCATION OF THE RIVER DEE CATCHMENT AREA AND THE 16 SUBCATCHMENTS REFERRED TO IN THE TEXT

nearby observations in four categories of wind direction, N to E, E to S, S to W, and W to N, and three categories of speed, 0–15 kt, 15–25 kt, and more than 25 kt. (The possible situation that all of the relevant surface winds were exactly south or west for example, thus making classification difficult, did not occur in this analysis.)

Early in the analysis it was found that when the surface wind speed was more than 15 kt the actual speed was not a significant factor in determining the distribution of rainfall within the Dee Catchment. (Not enough heavy rainfalls occurred when the wind speed was less than 15 kt to allow a decision on the importance of light wind speeds to be made.) Therefore only surface wind direction on a four-point compass (SW means winds between S and W) is discussed here.

Six synoptic types were classified: pre-warm-front; warm sector (including rain ahead of cold fronts); post-cold-front; occlusions; cyclonic rain not associated with well-defined frontal systems; and showers (with or without thunder) not associated with any other type. Periods during which the synoptic type and surface wind direction were constant are referred to as weather types in the following; they lasted between 3 and 36 hours approximately. For each weather type the areal rainfall for the whole of the Dee Catchment and for each of 16* subcatchments was computed by the method described by English.[2] Occasions when snow may have fallen or may have been lying in the gauges have not been included in the analysis.

Graphs were plotted of catchment rainfall against subcatchment rainfall for the different weather types. They showed that a linear relationship existed between the two parameters, so a line of best fit, correlation coefficient and standard error of the estimate were calculated for each subcatchment and weather type.

Examples of the data from two subcatchments for warm-sector rain with south-west winds are shown in Figure 2. The total number of rain periods in this category was 52. These graphs and those for each subcatchment for this weather type are summarized in Table I. The scatter about the line of best fit is expressed in two ways. In column 4 the standard error of estimate of R_s is shown in millimetres. In column 5 the error is expressed as a percentage of the mean fall over each subcatchment calculated from the 52 occasions. Averages of the errors shown in columns 4 and 5 are 2·3 mm and 33 per cent respectively. These values are indicative of the errors to be expected in a forecast of subcatchment rainfall, and they show that in the particular type of situation under consideration, the distribution of the rainfall over the subcatchments could be predicted with a fairly high degree of accuracy, provided that the rainfall over the entire catchment could be correctly forecast.

Table II summarizes some of the statistical parameters for the 10 weather types in which sufficient rain fell for significant regression equations to be calculated. Data for three subcatchments, which are representative of the 15, are presented. These results show that the scatter in the relationships in frontal rains is generally similar to those in Table I. Not surprisingly the scatter is

******Note:* **The results from subcatchment 12 will not be discussed since the small number of gauges in the area made it difficult to obtain accurate areal estimates over the subcatchment; the catchment estimate should not be significantly influenced by the sparser network in this region.**

TABLE I—WARM-SECTOR RAINS WITH SOUTH-WEST WINDS

Subcatchment	Slope of line of best fit R_s/R	Correlation coefficient	Standard error of estimate of R_s (S_s) *millimetres*	$S_s/\bar{R}_s$ *per cent*
1	0·66	0·85	2·3	42
2	0·73	0·88	2·2	38
3	1·01	0·95	1·8	24
4	1·35	0·97	2·0	20
5	1·76	0·89	5·2	38
6	1·74	0·92	4·2	32
7	1·55	0·96	2·5	23
8	1·44	0·97	2·2	25
9	1·12	0·99	0·9	13
10	1·04	0·96	1·9	29
11	0·71	0·88	2·3	54
13*	0·52	0·86	1·8	54
14	0·59	0·89	1·8	48
15	0·77	0·96	1·3	29
16	0·77	0·95	1·5	27
Average values			2·3 mm	33%

* Subcatchment 12 has been omitted.

largest in the eight occasions of showery rain which did not fit into one of the other classifications. In this class there appeared to be little or no systematic effect.

The results also show that the orographic effects are strongly dependent on weather type. The variability of rainfall on the scale of subcatchments is most marked within warm sectors and least marked ahead of warm fronts when the surface wind is south-westerly (see Table II). These findings are consistent with the conclusions of Browning *et alii*,[3] which were based on a very limited, but extensively analysed, number of cases.

The preceding statistical results have been computed for rainfall totals from periods of constant weather type. Falls from a few of the wetter storms shown in Figure 2 have been subdivided into hourly totals to investigate the extent to which these climatological rules are applicable to shorter periods within the storms. An example of the results obtained is shown in Figure 3. The line of best fit has a slope of 1·57 with a standard error of estimate(S) of 0·82 mm and an S/R_s of 30 per cent. So even on this short time-scale the distribution of rainfall can be predicted to a quite high degree of accuracy, provided that the large-scale rainfall can be forecast perfectly over the whole catchment.

Implications. The results of this investigation show that in general the amount of rain falling in a given synoptic situation over any subcatchment of the upper portions of the River Dee is closely related to the rainfall over the entire catchment. That is to say, given the large-scale (synoptic-scale) precipitation, the topography is by far the most important factor in controlling the distribution of rainfall in this area. The finding has important implications in forecasting rainfall amounts over subcatchments for hydrological purposes. Evidently the accuracy of forecasts of rainfall on the scale of subcatchments depends primarily

TABLE II—VARIATION OF SLOPES OF LINES OF BEST FIT FOR VARIOUS SYNOPTIC TYPES

Synoptic type	Wind direction	Number of observations	Subcatchment 6 R_6/R	Subcatchment 6 Standard error of estimate (S_6) mm	Subcatchment 6 $S_6/\bar{R}_6$ per cent	Subcatchment 9 R_9/R	Subcatchment 9 Standard error of estimate (S_9) mm	Subcatchment 9 $S_9/\bar{R}_9$ per cent	Subcatchment 14 R_{14}/R	Subcatchment 14 Standard error of estimate (S_{14}) mm	Subcatchment 14 $S_{14}/\bar{R}_{14}$ per cent
Pre-warm-front	SE	13	0·98	2·9	24	1·03	0·7	9	0·94	1·6	30
	SW	22	1·71	3·3	36	1·09	0·7	15	0·68	1·2	51
Warm sector	SE	9	2·50	4·7	28	1·05	0·8	9	0·46	1·9	38
	SW	52	1·74	4·2	32	1·12	0·9	13	0·59	1·8	48
Post-cold-front	SW	19	1·33	2·6	33	0·90	1·2	21	0·72	1·5	32
	NW	19	1·29	1·5	29	0·99	0·9	23	0·86	1·0	27
Cyclonic rains	SW + NW	24	1·10	3·0	29	1·11	1·0	14	0·76	2·1	41
	SE + NE	18	1·14	3·3	25	1·07	3·7	32	0·91	3·5	33
Occlusions	Various	21	1·17	3·4	36	0·88	2·3	35	0·65	1·9	38
Showers and thunderstorms	Various	8	0·03	3·4	79	2·22	2·2	38	1·19	2·8	69

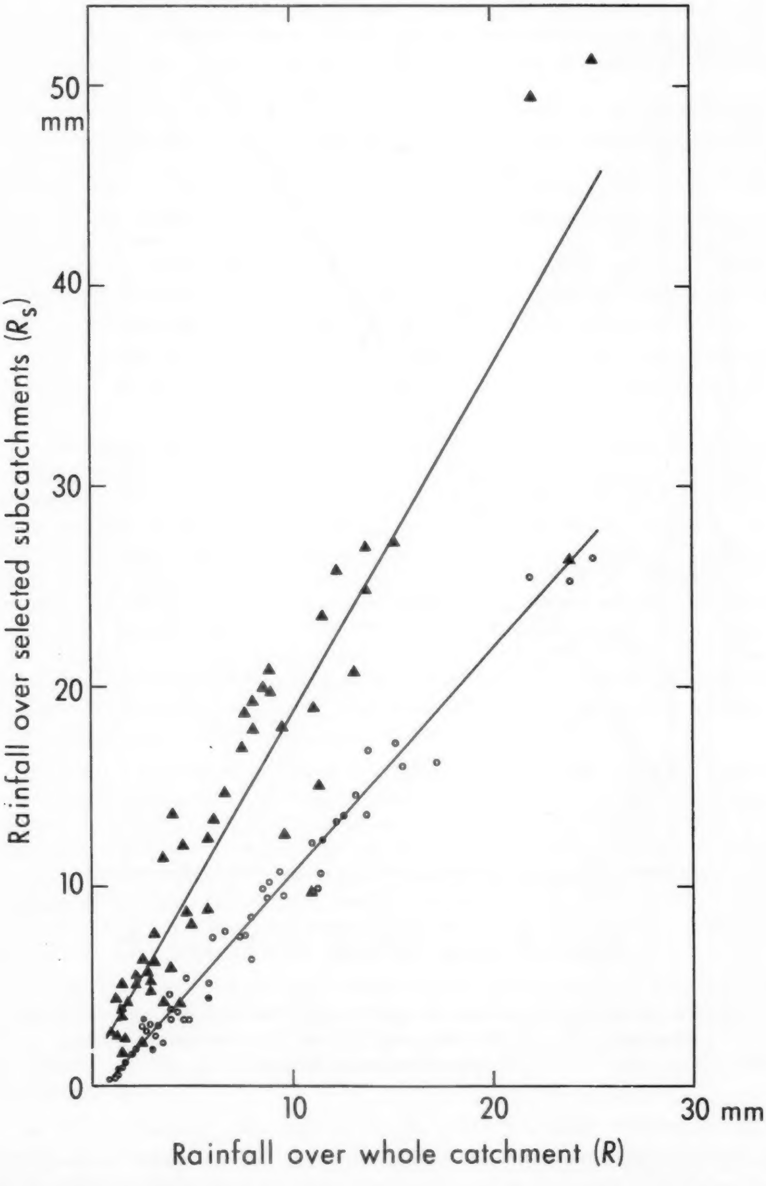

FIGURE 2—RAINFALL IN AREA 6 (▲) AND AREA 9 (○) PLOTTED AGAINST AVERAGE RAINFALL FOR ENTIRE AREA OF THE NETWORK (R) FOR WARM-SECTOR RAINS (AND RAIN AHEAD OF COLD FRONTS) WITH SOUTH-WEST WINDS

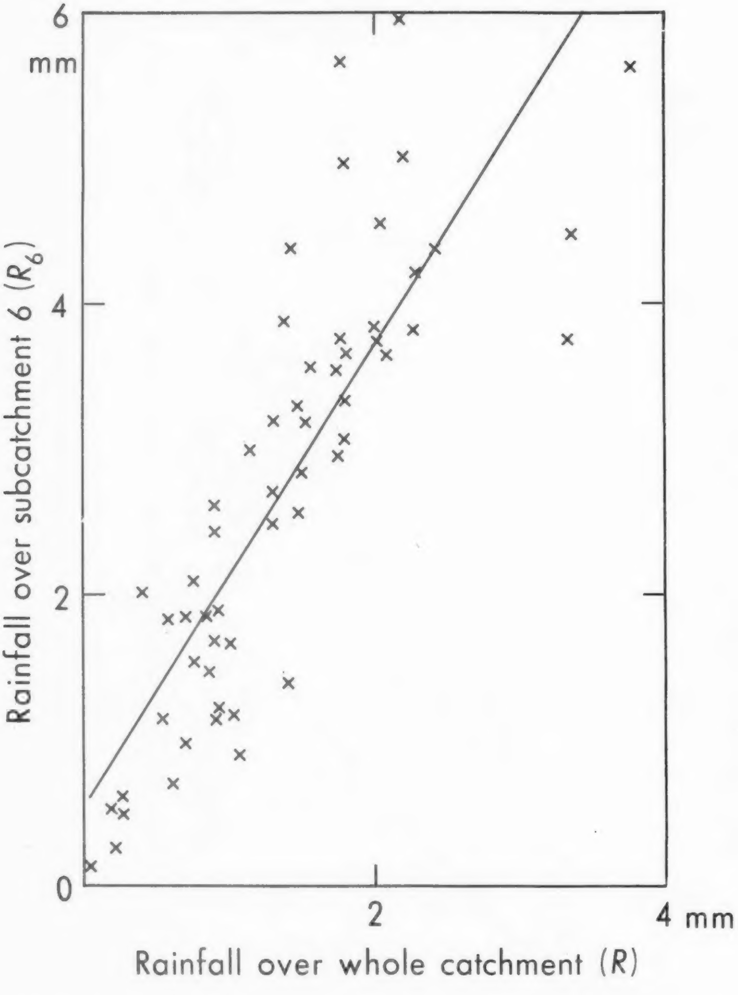

FIGURE 3—HOURLY RAINFALL IN AREA 6 (R_6) PLOTTED AGAINST HOURLY AVERAGE RAINFALL (R) FOR A SAMPLE OF THE WARM-SECTOR RAINS WITH SOUTH-WEST WINDS

on the accuracy with which the rainfall amounts over the entire catchment of 10^3 km^2 can be forecast. With this proviso that the large-scale rainfall can be accurately forecast, the distribution of rainfall within the catchment is reasonably predictable, particularly in frontal situations which produce by far the largest portion of the total rain in the area. The main exception occurs in

showery conditions. In addition, a mesoscale rain band not related to the topography (at least in its immediate vicinity) may occasionally dominate the frontal rainfall pattern for a period. Further research is needed in order to identify in advance occasions when such exceptions might occur.

The data were gathered over one particular hilly area. It is not known to what extent analogous synoptic climatological relationships apply in other hilly areas. However, the topography of the catchment of the Upper Dee is quite complex, with mountain ranges at several different orientations, so that the effects of the topography are complicated. Hence there is every reason to expect that similar well-defined relationships exist in other hilly areas. Unfortunately the data needed to determine such relationships cannot easily be obtained, since rainfall totals over small areas are required for periods of 'constant' synoptic type. Ways in which such data might be obtained are:

(a) to use existing autographic rain-gauge data. However, the density of autographic gauges is too sparse in almost all hilly regions to determine subcatchment rainfalls sufficiently accurately;

(b) to obtain additional rain-gauge data. This could be done by greatly increasing the density of autographic rain-gauges in areas of interest. However, the cost of collecting and analysing the data from an adequate network of such gauges in hilly terrain is high—£40 000 per annum for the Dee network. An alternative, simpler, means of obtaining the necessary data is to use quantitative rainfall measurements derived from weather radar (Harrold *et alii*[1]). The feasibility of doing this will be investigated using a mini-network of three quantitative weather radars during 1975 (Taylor and Browning[4]), but this network will only be operated occasionally for special research studies. A routine operational network of radars, such as discussed by Dee Weather Radar Project[5] would be required if radar were to provide the amount of data needed to determine climatological relationships over an extensive region; and

(c) to use a numerical model of the topographic effects on rainfall. Such a model has been described by Collier,[6] and Table III shows ratios of R_s/R over subcatchments of the Dee derived from this model in moving baroclinic disturbances, together with those from the rain-gauge network, for south-westerly winds. The average difference in R_s/R between these entirely different techniques is 21 per cent. However, it is not yet certain to what extent the model can be applied in other hilly areas; some independent data are required to investigate this.

It must be stressed that synoptic climatological relationships between rainfall amounts over subcatchments (typical area 60 km^2) to that over 1000 km^2 will only be of practical value if the rainfall amount over the 1000 km^2 can be accurately forecast. Possible methods of achieving reliable forecasts on the scale of 1000 km^2 are:

(a) to use existing numerical techniques with a smaller (mesoscale) grid length. It is not yet known what the smallest scale of accurate forecasts is but it seems improbable that it will be less than 10^3 km^2 in hilly terrain;

(b) to use climatological relationships similar to those described on page 210 to link the smallest scale accurately forecast in (a) to the scale of 10^3 km^2 (and hence 10^2 km^2). Suitable data do not exist at present for the determination

of relationships on this larger scale, but some should be forthcoming from the mini-network of research radars; and

(c) to use a parameterization such as Collier's[6] model to estimate the precipitation on a scale of 10^3 km^2 from an input of the larger-scale wind and humidity field, derived for instance from (a). This has been shown to be a successful technique over the Dee Catchment in moving baroclinic systems, using actual, rather than forecast, input parameters.

TABLE III—COMPARISON OF PREDICTED AND ACTUAL CLIMATOLOGICAL RATIOS FOR WARM-SECTOR RAINS WITH SOUTH-WEST WINDS

Subcatchment	R_s/R computed by Collier's[6] model	R_s/R measured by rain-gauges	$\frac{\text{Computed ratio}}{\text{measured ratio}}$ *per cent*
1	0·83	0·66	126
2	0·75	0·73	103
3	0·92	1·01	91
4	1·41	1·35	105
5	1·83	1·76	104
6	1·67	1·74	96
7	1·50	1·55	97
8	1·08	1·44	75
9	0·92	1·12	82
10	1·25	1·04	120
11	1·08	0·71	152
13	0·67	0·52	129
14	0·83	0·59	141
15	0·92	0·77	119
16	1·16	0·77	151

Mean absolute percentage difference = 21%

Conclusions. The analysis has shown that in most circumstances over the upper portion of the River Dee forecasts of the rain over subcatchments of area 20–100 km^2 could be forecast if there were a means of forecasting accurately over an area of 1000 km^2. It is considered that a similar conclusion would apply to other hilly terrain. Thus, if a method of forecasting rainfall over the larger area were developed this would also enable the hydrological requirement of quantitative rainfall forecasts over the smaller areas to be met.

However, there are several other forecasting requirements, for instance variations of rainfall intensity with time and also localized storms and stationary mesoscale rain bands which are not handled by the climatological rules. To meet these full requirements, it will probably be necessary to use results of the type presented in this paper in conjunction with real-time data from an operational network of weather radars.

Acknowedgements. The data used in this paper were collected and partly processed by the Welsh National Water Development Authority and the Water Data Unit, Reading as part of the Dee Weather Radar Project. The authors would like to acknowledge the assistance of Mr P. S. Shier (vacation student) in the analysis.

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CONFERENCE ON 'ENGINEERING HYDROLOGY TODAY', LONDON, 18–20 FEBRUARY 1975

By R. MURRAY

A conference on 'Engineering Hydrology Today' was held at the Institution of Civil Engineers in London from 18 to 20 February 1975 under the joint sponsorship of the Institution of Civil Engineers, the Institute of Hydrology, and the organizing committee of the International Hydrological Decade. The conference set out to review the contributions to the International Hydrological Decade (1965–74) made by the United Kingdom, with particular emphasis on results of relevance to engineering.

The conference was opened at 2 p.m. on the 18th by Lord Nugent, chairman of the National Water Council, who spoke briefly about the reorganization of the water industry which took place on 1 April 1974 as a consequence of the Water Act 1973. It was appropriate that Sir Norman Rowntree, erstwhile Director of the former Water Resources Board, which ceased to exist on 31 March 1974 as a result of the Act, should give the last talk on 'Summing-up and a look to the future'. Between the contributions of Lord Nugent and Sir Norman Rowntree, the conference was organized into six sessions which dealt with Organization, Instrumentation and Techniques, Meteorology, Flow Models, Flow Frequency Estimation, and Storage. There were three papers directly concerned with meteorology, namely (a) 'Determining precipitation, evaporation and soil moisture' by Dr. J. C. Rodda (Water Data Unit) and Mr J. F. Keers (Meteorological Office), (b) 'The variability of precipitation and evaporation' by Mr J. F. Keers and Dr J. C. Rodda and (c) 'Estimation of irrigation needs' by Mr B. G. Wales-Smith (Meteorological Office). All three papers were well received by an audience of nearly 200.

Dr Rodda, who introduced the first paper, demonstrated progress by the developments in measuring rainfall by radar (a major part having been played by the Meteorological Office team in the co-operative Dee Weather Radar Project) and in neutron probes, although Dr Penman was quick to point out that neutron probes were not novel to the Decade. Dr Rodda had to confess,

however, that rainfall continued to be measured for the most part by conventional gauges, but mentioned the Kew gravimetric gauge as a standard against which other types of gauge could be compared. There was lively discussion about the accuracy with which rainfall was measurable in different regions: in particular Mr Reynolds of the North of Scotland Hydro-electric Board thought that Dr Rodda was much too pessimistic in quoting a 20 per cent difference between readings in hilly terrain from the Meteorological Office Mk 2 rain-gauge sited in the standard way and the pit gauge with its rim at general ground level. Support for the accuracy of readings from the Mk 2 gauge, properly sited, came from Dr Penman and others. Nevertheless, it was felt that the problem of accurately measuring rainfall was still with us, especially over difficult terrain, although it was recognized that useful areal estimates could be obtained by radar. Snow measurement continued to be an unsolved problem. The need to improve the reliability of recording gauges, which generally have too high a failure rate, especially in freezing weather, was stressed by several delegates.

Mr Keers introduced the second paper but concentrated mainly on rainfall variability. A useful account was given of the different time and space scales of rainfall variability, with some reference to the precipitation mechanisms and underlying causes. He drew attention to some results of the work done by British radar meteorologists, notably Browning and Harrold, during the Decade, and referred briefly to the Meteorological Office's 'Project Scillonia' and the recent Global Atmospheric Research Programme Atlantic Tropical Experiment (GATE) during the summer of 1974, in which the United Kingdom, notably the Meteorological Office through the Meteorological Research Flight, played an important part. Mr Keers also touched upon the recently completed *Flood Studies Report*, but detailed discussion of this report was reserved for a conference at the Institution of Civil Engineers in May 1975.

Mr Wales-Smith surveyed a very wide field in his written paper but sensibly curtailed his spoken presentation and concentrated for the most part on studies in hand within the Meteorological Office. These studies concerned improvement of the 'Estimated Soil Moisture Deficit' (SMD) bulletin by means of the incorporation of a more realistic land-use model and by an improved computer-based system for accessing all types of up-to-date data needed for full exploitation of the Penman formula which constituted the scientific basis of the Meteorological Office's SMD bulletin. Brief reference was also made to rainfall deficiency studies and to other investigations. All such work should make it feasible to monitor soil moisture deficits more efficiently throughout the country and should help therefore in the monitoring of irrigation needs, especially if weather forecasts were sensibly used in connection with the latest SMD information.

The two papers presented by Keers and Wales-Smith were discussed together and provoked a lively discussion amongst hydrologists and engineers. At one point there was danger of the discussion straying too far into the field reserved for discussion at the conference on the *Flood Studies Report* in May 1975, but this clearly indicated the need felt by engineers for information on flood-producing rainfall, especially rainfall of short duration, information which is important in planning drainage systems. The need for informed advice on rainfall to engineers engaged on projects in hilly areas was mentioned. The lack of information on the variability of evaporation, comparable to the information on the variability of precipitation, was also mentioned in the discussion. Several

speakers clearly indicated the importance of work on evaporation and on soil moisture deficits to water resources management and indeed to civil engineers. Mr N. J. Cochrane (Sir William Halcrow and Partners) stressed the need for more information about evaporation and soil moisture conditions. Incidentally Mr Cochrane mentioned that neutron probes had been used—without much success owing to difficulties of maintenance and power supply—in two road-building projects in Africa many years ago. However, there was little doubt that under reliable management neutron probes were now reliable instruments.

Other important papers by hydrologists and engineers on 'Catchment modelling to estimate flows', 'Open-channel hydraulics', 'Flow frequency estimates', 'Groundwater yield estimates from models' and 'Assessment of surface water sources' were not so directly of interest to meteorologists, although the meteorological input (precipitation and evaporation) is of great importance. It was interesting to a meteorologist to learn that some of the engineers and practical hydrologists were rather sceptical about the value of complicated mathematical models and seemed to prefer empirical models, based on data and experience. There was also a feeling of distrust among some delegates of synthetic-data generation, especially in view of the amount of rainfall data, and to a less extent stream-flow data, available in the United Kingdom.

The conference was particularly appreciated by the three Meteorological Office representatives who were able to meet engineers and hydrologists and to learn about some of their practical problems and their meteorological requirements, as well as to enjoy accounts of some British achievements in hydrology during the recent Decade.

PUBLICATIONS RECEIVED

The following have been received from the Meteorological Institute of the University of Thessaloniki:

Meteorologika 36: *Nature of the diurnal variation of atmospheric pressure in Thessaloniki.* By T. J. Makroyannis. 1974.

Meteorologika 37. *Cooling power and weather types in Thessaloniki.* By Chr. J. Balafoutis. 1974.

Meteorologika 38: *On the effect of ground relief upon sunshine duration on Mount Olympus—Greece.* By G. C. Livadas and V. A. Semertzidis. 1974.

Meteorologika 39: *On the annual variation of air temperature in Thessaloniki.* By A. A. Flocas and A. Arseni-Papadimitriou. 1974.

Meteorologika 40: *Contribution to the study of air temperature in Thessaloniki.* By A. Arseni-Papadimitrou. 1974.

Meteorological Magazine: price increases

As from July 1975 the price of an issue of the *Meteorological Magazine* will be 40p and the annual subscription will be £5.46 including postage.

NOTES AND NEWS

Retirement of Mr J. M. Craddock

On 4 June 1975 Mr James Marston Craddock retired from the Meteorological Office after 33 years' service. For the previous 16 years he had been a Special Merit Senior Principal Scientific Officer concerned with the application of statistics and computers to long-range weather forecasting.

Mr Craddock joined the Office in 1942 on secondment from the Inland Revenue Department, having previously taken a first-class degree in mathematics at Cambridge University where he was a scholar of Magdalene College, and spent the next five years of his career as a forecaster. After a short spell at Prestwick he was posted to the upper-air bench at Dunstable. He was then commissioned as a Flight Lieutenant in the Royal Air Force and posted to the Far East where he spent about a year in Singapore before moving to Butterworth.

On demobilization in 1947, Mr Craddock, having decided that he would get more satisfaction from meteorological research than from returning to the Inland Revenue, was posted as a Senior Scientific Officer to Dunstable and was one of the first members of Dr Sutcliffe's forecasting-research group in the Napier Shaw Building. Mr Craddock had clearly found his niche in life and, apart from a two-year spell in 1953–54 when he was posted to the Central Forecasting Office as a senior forecaster on his promotion to Principal Scientific Officer, he continued to work in the research branch connected with long-range weather prediction until his retirement. In 1959 he obtained a well-deserved special merit promotion to Senior Principal Scientific Officer. In addition he received the L. G. Groves and Darton Prizes in recognition of his scientific ability.

Two of Mr Craddock's major achievements in the Office have been the development of sound statistical methods for use in meteorological research and the application of computers to the operational and research work of the Synoptic Climatology Branch. In the statistical field Mr Craddock has made important contributions on topics such as the analysis of time series and the application of principal component analysis to meteorological problems. In the computer field he has been largely responsible for building up a large long-range data bank and for developing the METOCODE language which has considerably reduced the amount of programming effort required to permit statistical programs to be run on the computer. In addition, Mr Craddock has been a World Meteorological Organization consultant concerned with the collection, storage and cataloguing of meteorological literature and data.

We all wish Mr and Mrs Craddock many years of happy retirement.

F. H. BUSHBY

THE METEOROLOGICAL MAGAZINE

VOL. 104 NO. 1236 JULY 1975

CONTENTS

Page

Lerwick anemograph records 1957–70 and the offshore industry. H. C. Shellard 189

The distribution of rainfall over subcatchments of the River Dee as a function of synoptic type. C. A. Nicholass and T. W. Harrold 208

Conference on 'Engineering Hydrology Today', London, 18–20 February 1975. R. Murray 217

Publications received 219

Meteorological Magazine: price increase 219

Notes and news

Retirement of Mr J. M. Craddock 220

NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'For Meteorological Magazine'.

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